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RESEARCH MEMORANDUM

ALTITUDE-CHAMBER EVALUATION OF AN AIRCRAFT LIQUID-HYDROGEN FUEL SYSTEM USED WITH A TURBOJET ENGINE

By Willis M. Braithwaite, David B. Fenn, and Joseph S. Algranti

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
August 19, 1957

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

ALTITUDE-CHAMBER EVALUATION OF AN AIRCRAFT LIQUID-HYDROGEN FUEL-SYSTEM USED WITH A TURBOJET ENGINE

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SUMMARY

A flight-type fuel system was designed to serve a turbojet engine using liquid hydrogen. The fuel system permits engine operation on hydrogen, JP-4 fuel, and combinations of the two introduced separately into the engine. This fuel system was evaluated in an NACA altitude test chamber to determine its reliability and to make final adjustments prior to installation in a twin-engine light bomber. This evaluation was confined to operation at altitudes from 47,000 to 50,000 feet and a Mach number of 0.75, the conditions selected for the subsequent flight test. The principal characteristics evaluated were the ability of the system to make transitions between JP-4 fuel and hydrogen, the ability of the system to control engine speed, and the effect of hydrogen on engine performance.

The fuel system consisted of (1) a stainless steel wingtip fuel tank for liquid hydrogen, (2) a ram-air heat exchanger to vaporize the fuel, and (3) a regulator for the hydrogen flow, which was controlled by the regular engine throttle. The engine was modified to the extent of adding a separate fuel manifold and injection tubes for the hydrogen.

Over three-fourths of the 38 transitions from JP-4 fuel to hydrogen were satisfactory. The other transitions were characterized by speed variations. However, these variations were small and were considered not to have a detrimental effect on aircraft performance. The engine performance at limiting speed and turbine-inlet temperature was not affected by the use of hydrogen.

INTRODUCTION

The problems associated with use of hydrogen as a high-energy fuel for obtaining increased range and altitude capabilities for military aircraft are being studied now. An analysis of the performance possibilities of liquid hydrogen for increasing the range and operating altitudes of several types of aircraft is presented in reference 1. The characteristics of liquid hydrogen that indicate its great potential as an aircraft fuel include the high heat of combustion, stable and efficient burning at low pressures, and excellent heat-sink capacity that can be utilized in cooling the engine and aircraft structures at high flight speeds.

To obtain further information on the problems and handling characteristics of hydrogen fuel for aircraft use, a program was established to use hydrogen fuel in a flight of a bomber aircraft. The project involved the modification of a twin-engine light bomber aircraft to include a hydrogen fuel system. The hydrogen was stored as a liquid, vaporized by means of a ram-air heat exchanger, and burned in the combustor, which was modified to permit interchangeable use of JP-4 fuel and hydrogen. The complete liquid-hydrogen fuel system described was evaluated in combination with a turbojet engine in an NACA altitude facility prior to the flight test. 4602

The objectives of this report are (1) to describe the complete fuel system, (2) to discuss the procedure used for transitions between JP-4 fuel and hydrogen, (3) to present and discuss engine performance obtained with both fuels, and (4) to review the reliability of the fuel system.

APPARATUS

Fuel System

The fuel-system design was based on the flight application. There were three basic considerations: (1) the aircraft would take off and climb on JP-4 fuel, change to hydrogen fuel in one engine and cruise for the duration of the fuel supply, and then change back to JP-4 fuel in that engine for return and landing, (2) the controls of the system should be as simple as would be consistent with reliability and safety, and (3) the system should be tailored to fit the bomber aircraft that had been selected for the flight phase of the program and to the selected flight conditions (altitudes from 47,000 to 50,000 ft at a flight Mach number of 0.75).

The fuel system (shown schematically in fig. 1) consisted of individual components based on the information obtained from the investigations of references 2 to 4 and was installed in an altitude facility (fig. 2(a)). The hydrogen was stored as a liquid in a stainless steel wingtip fuel tank (described in ref. 2) having a capacity of 430 gallons (approx. 250 lb) (fig. 2(b)). This tank was insulated with plastic foam only, since the liquid would be stored in it just a short time.

The liquid hydrogen was fed under helium gas pressure from the fuel tank to the bottom of the heat exchanger through a vacuum-jacketed stainless steel line. The vaporized hydrogen was collected in the top of the heat exchanger and then fed to the hydrogen regulator. From the regulator the hydrogen flowed to the manifold on the engine and into the combustor through extra injection tubes described in the section Engine and Engine Modifications.

The liquid hydrogen was vaporized in a crossflow heat exchanger (described in ref. 3) designed to evaporate 520 pounds of liquid hydrogen per hour with 1.75 pounds of air per second. The heat exchanger was sized to ensure that the air would not be liquefied. The 28 tubes of the heat exchanger were commercially available, integral-fin, 5/8-inch-diameter copper tubes, 1 foot long.

4602 During operation on hydrogen the engine fuel control sensed engine speed and regulated the JP-4 fuel from the engine JP-4 fuel pump in the normal manner. This flow was fed to the automatic hydrogen regulator and then back to the JP-4 fuel tank. The hydrogen regulator is shown in figure 3 and is described in reference 4. The regulator consisted of two chambers. The JP-4 fuel flowed through one chamber, which contained an orifice for setting up a pressure drop as a function of flow and a piston that sensed the drop. The force developed was transmitted through a sealed connecting lever (with a ratio of 1:1) to the hydrogen side of the regulator, which contained an orifice, a piston, and a valve assembly. The hydrogen flow through the regulator acted on the piston to set up a balancing force. Any change in JP-4 fuel flow changed the forces applied to the piston and thus required a change in hydrogen flow to reestablish equilibrium. If an increase in hydrogen flow was required, a greater force was exerted on the JP-4 fuel piston, and this force was transmitted to the hydrogen side, where the valve was opened farther. In this manner the unit controlled the volume flow of hydrogen in a constant ratio to the flow of JP-4 fuel. The ratio used was that of the heating values of the two fuels, and it was obtained by selecting suitable values for the orifice and piston areas. Because the weight flow of hydrogen depends on its density, it was necessary to incorporate a density compensator. The method selected was to adjust the orifice area of the hydrogen piston with a helium-filled phosphor bronze bellows type thermostat (fig. 3).

The initial step in the transition from JP-4 fuel to hydrogen was a cooling period for the hydrogen fuel system, during which time the engine was operated on both hydrogen and JP-4 fuel. Because only part of the JP-4 fuel went to the engine and the remainder was bypassed back to the fuel tank during dual fuel operation, an orifice was installed in the JP-4 fuel bypass line ahead of the hydrogen regulator to control the split of JP-4 fuel. It was sized to divert approximately two-thirds of the JP-4 fuel flow from the engine to the regulator. A second orifice was installed in the line from the hydrogen regulator to the JP-4 fuel tank to give better control of the pressure in the regulator.

A special fuel control panel developed for the airplane was installed in the control room of the altitude facility (fig. 4). This panel contained, in addition to the normal instrumentation for engine operation, a transfer switch that programmed the opening and closing of the valves of the fuel system during transition from one fuel to the other, indicator lights to show whether valves were open or closed, and a temperature gage to indicate the temperature of the hydrogen at the outlet of the heat exchanger. There were several additional switches to control the fuel-leak detector and the heat-exchanger air-scoop flap. Next to the panel is shown the throttle, which operated the engine JP-4 fuel control, and through it, the hydrogen regulator and engine speed. Thus, for transition to hydrogen, the pilot required only two basic controls, the throttle and the transfer switch.

The hydrogen fuel system was assembled by conventional methods of fabrication. The materials used were copper, brass, and stainless steel, having been selected for their low-temperature strength and ductility characteristics. The valves used were commercial low-temperature types modified only for method of operation. Helium was substituted for air in the pneumatic operators as a safety precaution. 4602

Engine and Engine Modifications

The engine used for this investigation was a J65-W-5 turbojet engine (the same engine as used in the B-57 bomber in the flight program). The only modifications were an added separate manifold around the engine near the compressor discharge for the hydrogen fuel (fig. 2(a)) and an extra fuel injection tube in each of the vaporizer tubes of the engine combustor (fig. 5). The engine was equipped with a fixed-area exhaust nozzle, which was sized according to the engine manufacturer's specification to give rated exhaust-gas temperature at rated engine speed at sea level using JP-4 fuel.

Safety Precautions

For the safe handling of hydrogen, certain safety precautions were observed. The complete hydrogen fuel system was thoroughly purged with helium before and after each run, and helium, at a positive gage pressure, was trapped in the system between runs. All the fuel lines inside the building were shrouded by a larger pipe that was vented to the altitude exhaust system and to the atmosphere well away from the buildings (fig. 2(b)). All the joints in the fuel lines were checked before each run, and a continuous check was made during each run with a fuel-leak detector. Hydrogen was introduced into the engine only after the engine was operating on JP-4 fuel.

The fuel-leak detector was a thermal conductivity comparative fuel-air analyzer. Samples were taken in four general areas: joints in the fuel lines, the air outlet of the heat exchanger, the hydrogen regulator, and near the engine manifold. In addition, a portable instrument was used outside the building in the vicinity of the fuel tank, fuel lines, and vents during the time the fuel was being handled. Care was also taken to avoid sources of ignition in areas where fuel leaks could develop.

All electrical equipment that could spark was located away from this area or protected from the vapor, and the fuel system was grounded to prevent static discharges.

INSTRUMENTATION

Both transient and steady-state instrumentation were used to record fuel-system and engine performance. The transient instrumentation recorded fuel-system pressures, fuel temperature, JP-4 fuel flows, hydrogen-regulator position, engine speed, compressor-discharge pressure, and turbine-outlet temperature. Data recorded with steady-state instrumentation include pressures and temperatures required for engine performance analysis and hydrogen-fuel-system pressures and temperatures.

Temperatures of the cold fuel were measured with carbon resistors because of their relatively large voltage changes with temperatures below 140° R (ref. 3). Temperatures of the metal parts of the heat exchanger and the fuel tank were measured with copper-constantan thermocouples referenced to liquid nitrogen boiling at atmospheric pressure.

An attempt was made to measure the flow of hydrogen with a Venturi downstream of the heat exchanger. However, the data were unreliable because of large instantaneous temperature oscillations at the heat-exchanger outlet. These oscillations may be indicative of carry-over of liquid drops as well as vaporized hydrogen in the Venturi, which resulted in variations in density. Therefore, the fuel flow was computed from engine performance using a combustion efficiency of 98 percent, the value obtained in a small-scale burner using hydrogen gas at -400° F (ref. 5).

PROCEDURE

The transition from engine operation with JP-4 fuel to operation with hydrogen can best be described by reference to figure 6. The engine was stabilized at 96 percent rated engine speed on JP-4 fuel at the simulated altitude condition. The hydrogen fuel tank and fuel line were pressurized with helium. The hydrogen valve of the engine was opened in order to purge with helium any air that may have been in the hydrogen lines and manifold into the engine. After the system had been purged for 1 to 2 minutes, the system was ready for transition.

To start the actual transition, the JP-4 fuel valve to the hydrogen regulator was opened to permit JP-4 fuel to flow through. Simultaneously, the purge valve was closed, and the hydrogen tank valve was opened to allow hydrogen to start flowing through the system to the engine. Since the hydrogen system at the start was warm, the initial hydrogen flow in the dual fuel operation served to cool the system to its operating condition.

To reduce the cool-down time to a minimum, the heat-exchanger airflow was maintained below the design value until the temperature of the hydrogen leaving the heat exchanger decreased to about 140° R. Also, because of the relatively high hydrogen temperature, the hydrogen fuel flow alone was not sufficient to maintain engine speed. The dual flow of JP-4 fuel and hydrogen was continued to the engine until the hydrogen temperature had stabilized. As a result, approximately 2 minutes of operation on both JP-4 fuel and hydrogen were required. The transition was completed 4602 by closing the JP-4 fuel valve. This forced all the JP-4 fuel from the engine control through the hydrogen regulator back to the JP-4 fuel tank. After the engine was operating completely on hydrogen fuel, the engine speed could be varied by normal manipulation of the engine throttle.

To transfer back to JP-4 fuel, the hydrogen tank valve and the JP-4 fuel valve to the hydrogen regulator were closed. Simultaneously, the JP-4 fuel valve to the engine and the purge valve were opened. Thus the flow of hydrogen from the tank was stopped, and the flow of JP-4 fuel was started to the engine. The hydrogen remaining in the fuel lines was purged into the engine with helium.

RESULTS AND DISCUSSION

The performance of the hydrogen fuel system during steady-state operation on hydrogen fuel and during transition from JP-4 fuel to hydrogen is described in this section. Because the effect of using hydrogen as a fuel for this engine is discussed in references 6 and 7, only a brief comparison is given of engine performance on JP-4 fuel and hydrogen for the flight conditions selected.

Fuel System in Steady State

The hydrogen regulator was designed to require approximately the same JP-4 fuel flow as normally used by the engine at the same speed. The ratio of the JP-4 fuel flow required by the regulator to the flow required by the engine at the same speed is shown in figure 7(a). The JP-4 fuel flow required by the hydrogen regulator was approximately 10 percent lower than the scheduled flow in the range from 96 to 100 percent rated speed, where most of the operation occurred, and was about 20 percent lower at 92 percent rated speed. These deviations from the control schedule were sufficiently small that the engine speed was controlled over this speed range.

The JP-4 fuel flow required by the hydrogen regulator was also affected by the density of the hydrogen. The regulator was primarily a volumetric control during steady-state operation. The density compensator, designed to adjust the volume flow of gaseous hydrogen during the cool-down phase, was fully closed at the low hydrogen temperatures (approx. -380° F) which occurred during steady-state operation. Therefore, variations in the density of the hydrogen passing through the regulator resulted in variations in the heat supplied to the engine. Thus, when the hydrogen density increased, the heat supplied to the engine was increased. This resulted in increased engine speed. However, the JP-4 fuel control, sensing the increase in engine speed, decreased the JP-4 fuel to the control, which, in turn, decreased the volume flow of hydrogen until the desired speed was obtained.

4602 The density of the hydrogen during steady-state operation was a function of the heat-exchanger operation (ref. 3). As the airflow through the heat exchanger was reduced from the design value (1.75 lb/sec), the temperature of the hydrogen leaving the heat exchanger decreased. When the heat-exchanger airflow was reduced sufficiently, the hydrogen entering the regulator was a two-phase mixture. The effect of the hydrogen density on the JP-4 fuel flow required to maintain a constant engine speed is shown in figure 7(b) as a function of heat-exchanger airflow. Thus, the JP-4 fuel flow required by the hydrogen regulator to maintain a given engine speed varied 12 percent for the range of heat-exchanger airflow investigated. The JP-4 fuel control had sufficient range to maintain control of the engine over this range of operation.

The pressure levels in the fuel system are shown in figure 8. The major pressure drop in the JP-4 fuel part of the fuel system (fig. 8(a)) occurred in the orifices, while the major drop in the hydrogen system occurred in the hydrogen regulator (fig. 8(b)). The pressure in the hydrogen tank was held at approximately 54 pounds per square inch absolute, while the pressure in the engine combustor was approximately 22 pounds per square inch absolute.

Fuel-System Transitions

A typical transition from JP-4 fuel to hydrogen is shown in figure 9. The first part of the transition was the purging of the system with helium. The speed increased momentarily, and the JP-4 fuel flow decreased because of the ejection of the JP-4 fuel that had accumulated in the separate hydrogen manifold during engine operation with JP-4 fuel. The next step in the transition was to divert part of the JP-4 fuel to the hydrogen regulator and start the flow of hydrogen. The engine speed fell off because of the loss of JP-4 fuel and recovered when hydrogen reached the engine. The JP-4 fuel flow became stable with about two-thirds of the JP-4 fuel going to the regulator. During this time the hydrogen fuel temperature decreased, until a temperature of approximately 80° R was reached. The last step was to divert all the JP-4 fuel to the regulator. This resulted in a slight speed drop until steady flows were reestablished and the hydrogen temperature dropped to approximately 55° R.

The transition shown in figure 9 is typical of about three-fourths of 38 transitions made with the final fuel system. The remainder of these transitions were to some extent unstable, as shown by the speed and

pressure variations in figure 10. The engine speeds varied ±125 rpm (±1.5 percent), while the pressure variations at several locations in the fuel system were as follows: fuel tank, ±1/2 pound per square inch absolute; heat-exchanger inlet, $\pm 7\frac{1}{2}$ pounds per square inch absolute; heat-exchanger outlet, ±5 pounds per square inch absolute; and compressor discharge, $\pm 1\frac{1}{4}$ pounds per square inch absolute. The pressure variations in 4602
the heat exchanger and the compressor discharge were in phase, while the variations in speed lagged by 1/2 second. These variations damped out in approximately 10 minutes or less.

It was thought that this instability originated in the heat exchanger and was a function of the dynamics of the control loop. Two system modifications were investigated, and the fluctuations in engine speed during hydrogen operation are shown in figure 11. The earlier configuration had a line from the tank to the heat exchanger 90 feet long and from the heat exchanger to the engine 3 feet long. In the final configuration the line from the tank to the heat exchanger was 20 feet long and that from the heat exchanger to the engine was 6 feet long. These changes in line lengths resulted in a change in frequency of speed variation from 2 to 8 cycles per minute. Although not generally acceptable, these instabilities could be tolerated for the flight tests of this initial hydrogen fuel system because their effect on aircraft performance was small. The higher frequency variations shown on both speed traces had a frequency of 12 to 14 cycles per second, values approximately equal to the undamped natural frequency of the control loop (ref. 4). That this is the natural frequency is further substantiated by the damping which occurred between the major disturbances.

Engine Performance

The effects of hydrogen as a fuel on engine performance are discussed in references 6 and 7. Therefore, this report presents only a brief summary of these effects with this engine fuel injection system. As stated previously, this engine was equipped with a fixed-area exhaust nozzle, sized for JP-4 fuel according to the manufacturer's specification. The effects of hydrogen on the turbine-inlet temperature distributions and on other engine performance parameters are shown in figures 12 and 13, respectively. A comparison of the turbine-inlet temperature profiles with hydrogen (fig. 12) indicates no significant change from those obtained with JP-4 fuel. The limiting value of turbine-inlet temperature (2000° R) was obtained at 98.2 percent of rated engine speed with JP-4 fuel and at 100 percent of rated speed with hydrogen at the test altitude and Mach number (50,000 ft, Mach 0.75). This resulted in a decrease in maximum net thrust from 1220 pounds with JP-4 fuel to 1215 pounds with hydrogen (fig. 13(a)). Therefore, for the two engines of the bomber aircraft the thrust from the engine using hydrogen would match that from the one using JP-4 fuel. Some of the engine performance parameters for hydrogen and JP-4 fuel are compared in figure 13(b). The compressor remained at the same operating condition at the same engine speed. Because of the change in gas properties with hydrogen, turbine-inlet temperature, turbine-outlet temperature, and pressure decreased. Therefore, the thrust at a given engine speed was lower with hydrogen than with JP-4 fuel. However, at limiting turbine-inlet temperature the thrust values obtained with hydrogen and JP-4 fuel were approximately equal.

The effect on fuel consumption of using hydrogen is illustrated in
4602 figures 13(c) and (d). At 98 percent rated speed the net-thrust specific fuel consumption with hydrogen was 0.387 that obtained with JP-4 fuel. However, this corresponds to an increase in volume consumption of more than $4\frac{1}{2}$ times. The lower ratios of weight of hydrogen to JP-4 fuel shown at lower engine speeds are due to the lower combustion efficiency with JP-4 fuel; the efficiency with hydrogen was assumed constant (ref. 5).

System Reliability

To determine the reliability of this fuel system, the engine was operated on hydrogen fuel for about 20 hours, during which 38 transitions from JP-4 fuel to hydrogen were made. The only damage to the system was slight heat warpage at the base of the vaporizer tubes (fig. 14). Aside from a few unstable transitions previously mentioned, the fuel system performed in a satisfactory manner.

It was felt that in flight the system might be subjected to conditions not exactly simulated in the altitude chamber. One such condition considered was that of the hydrogen regulator becoming inoperative in the closed position because of freezing of water, fuel, or other matter in the regulator. Therefore, this condition was simulated by reversing the JP-4 fuel flow through the regulator, which forced the regulator to close. The effect on a transition was determined and is shown as curve A in figure 15. The engine speed recovered during the dual fuel operation but could not be maintained on the hydrogen leakage through the regulator when the JP-4 fuel was diverted from the engine. A manually operated valve was installed so that the hydrogen regulator could be bypassed in such an emergency. The trace indicates that the engine speed could be controlled using this bypass. Trace B of figure 15 illustrates the effect on speed of initiating the transition at a reduced engine speed of 82 percent rated instead of 90 to 96 percent rated as was normal. Again the regulator was in an inoperative condition. The lower initial speed required a longer time for the engine to recover during dual fuel operation.

The final evaluation of this fuel system in the altitude test chamber was made by the test pilots. They operated the engine during the transition in the same manner as they would during flight. This was done to determine the adequacy of the regulator and the emergency procedures as well as to familiarize the pilots with the procedures. Following the evaluation of this system, the engine and complete fuel system were removed from the altitude facility and installed in the aircraft for flight testing. The flight tests are described in reference 8.

SUMMARY OF RESULTS

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A fuel system was developed for the use of hydrogen fuel in a twin-engine light bomber. This system, evaluated in an NACA altitude test chamber, consisted of (1) a wingtip fuel tank, (2) a ram-air heat exchanger to vaporize the fuel, and (3) a regulator utilizing the output of the regular JP-4 fuel control to regulate the flow of hydrogen. The engine was modified by addition of an extra manifold and an injection system for hydrogen. The controls required for this system consisted of the regular engine throttle and a switch that programmed the opening and closing of the valves in the proper sequence during the transition from JP-4 fuel to hydrogen.

Of the 38 transitions made during altitude-test-chamber evaluations, three-fourths were satisfactory in all aspects, while the other one-fourth were characterized by engine speed instability with hydrogen. However, these speed variations were so small and of such short duration that they were considered tolerable.

From the performance obtained in the evaluation in the altitude chamber, the fuel system was considered satisfactory for flight.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 13, 1957

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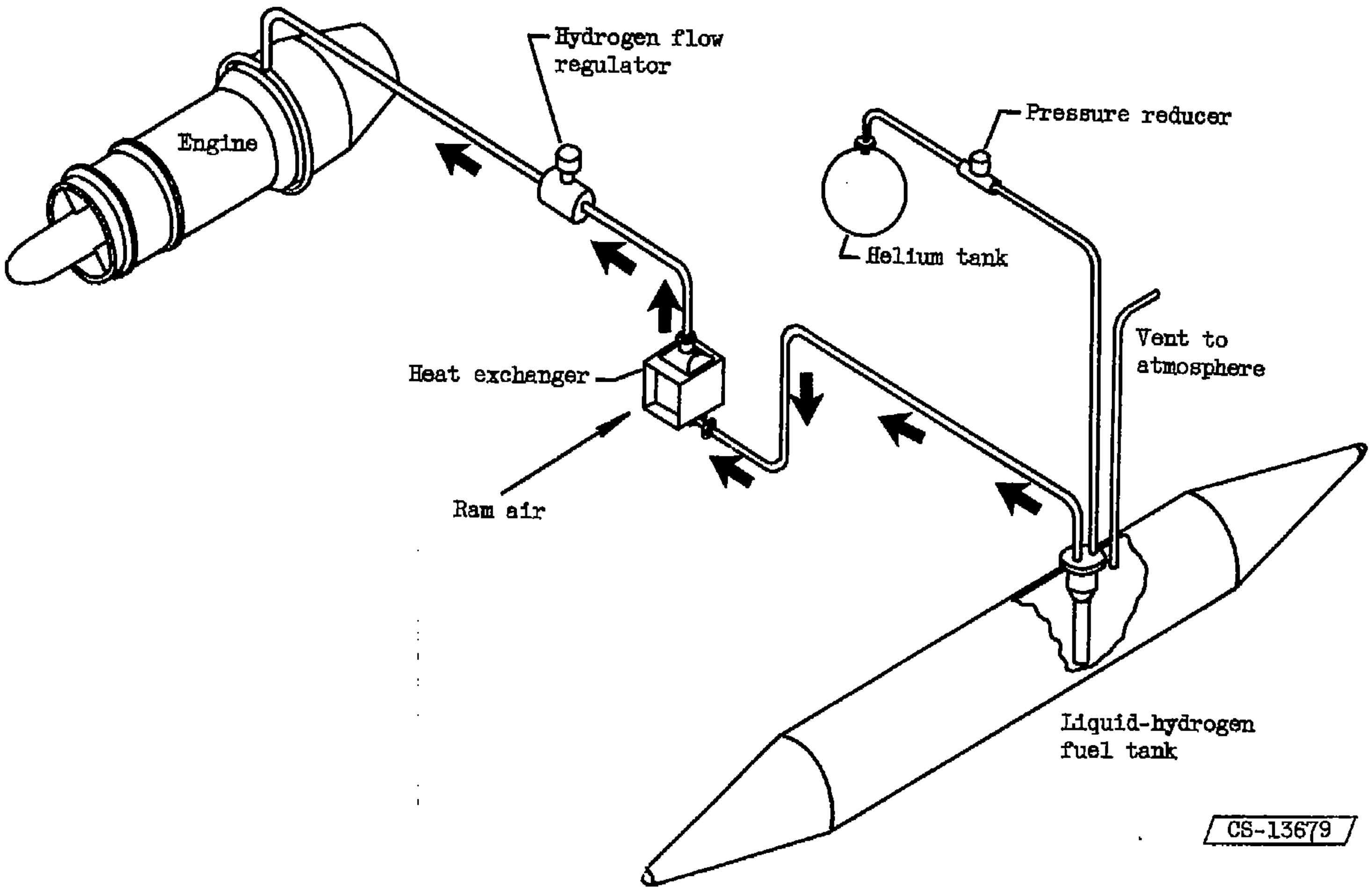
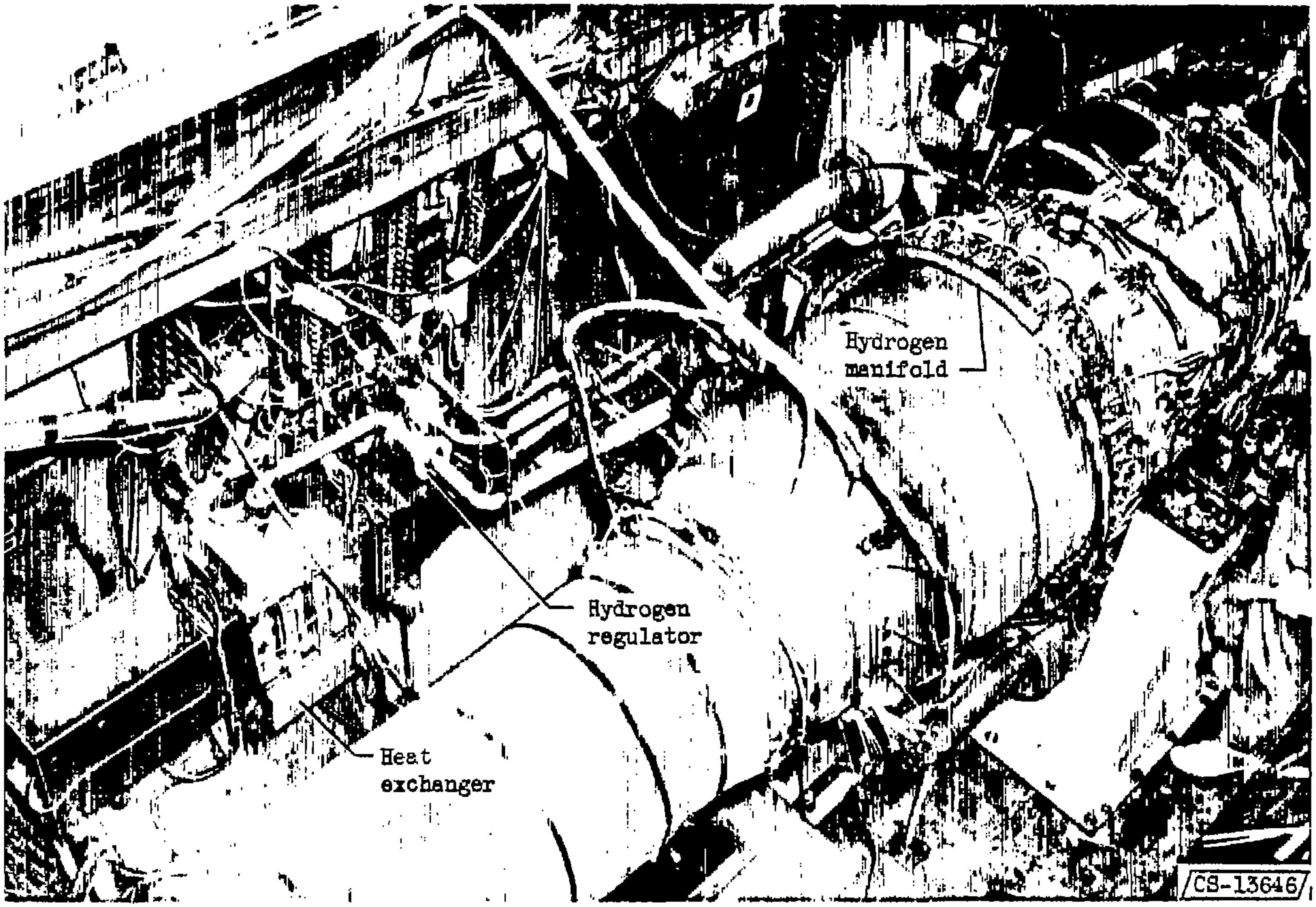
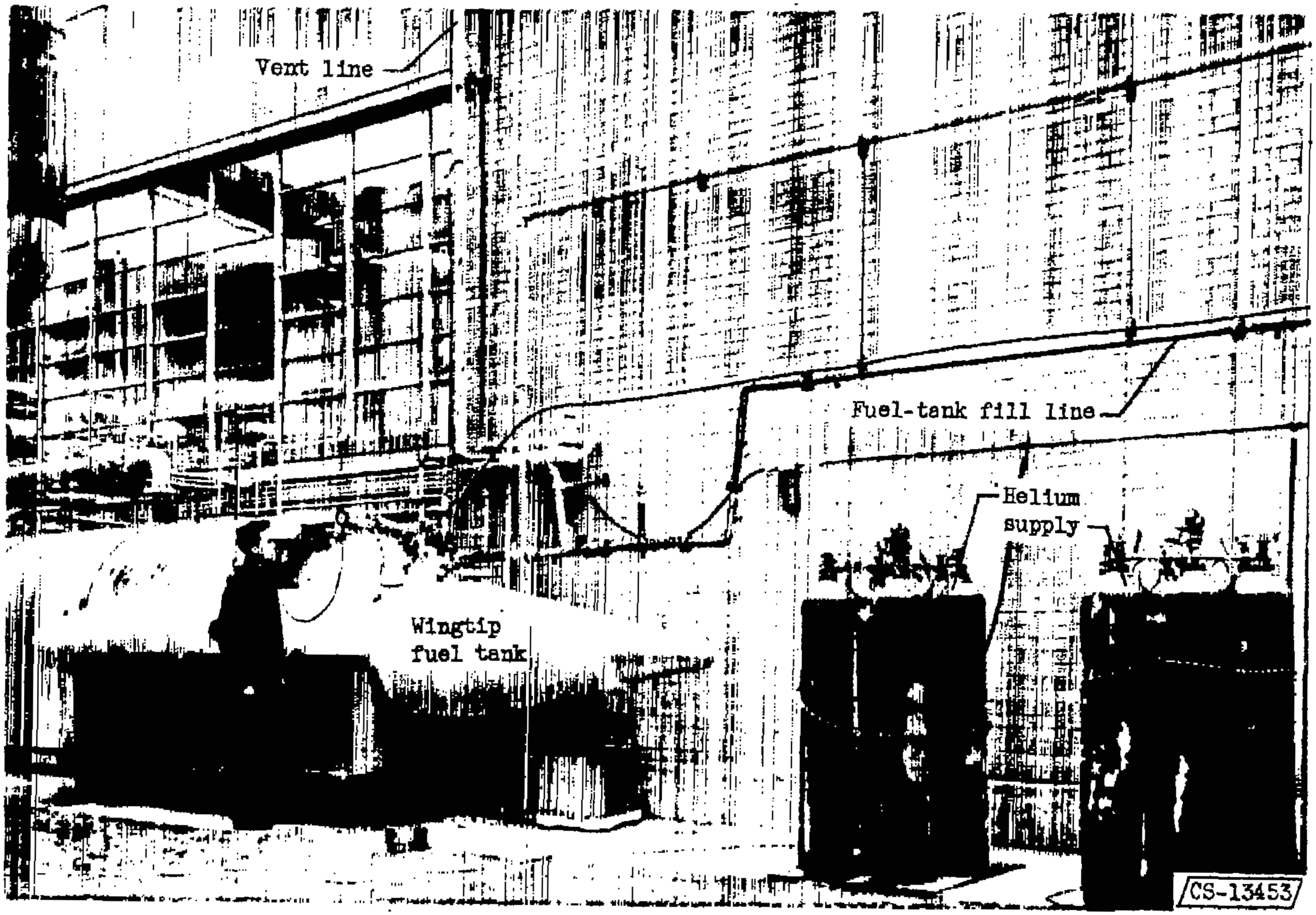


Figure 1. - Hydrogen flow system.



(a) Installation in altitude chamber.

Figure 2. - Installation of hydrogen fuel system and engine.



(b) Outside installation.

Figure 2. - Concluded. Installation of hydrogen fuel system and engine.

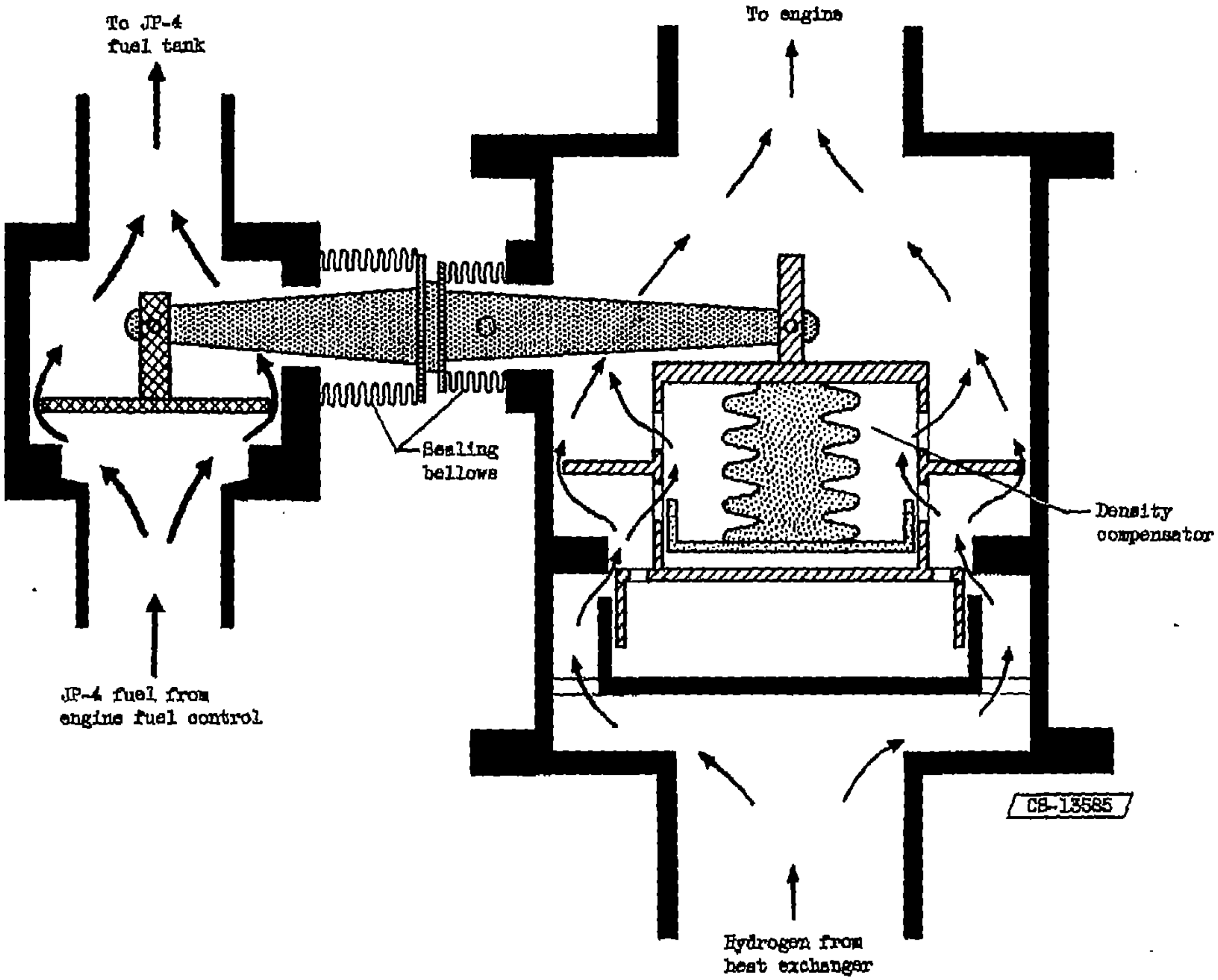


Figure 3. - Hydrogen flow regulator.

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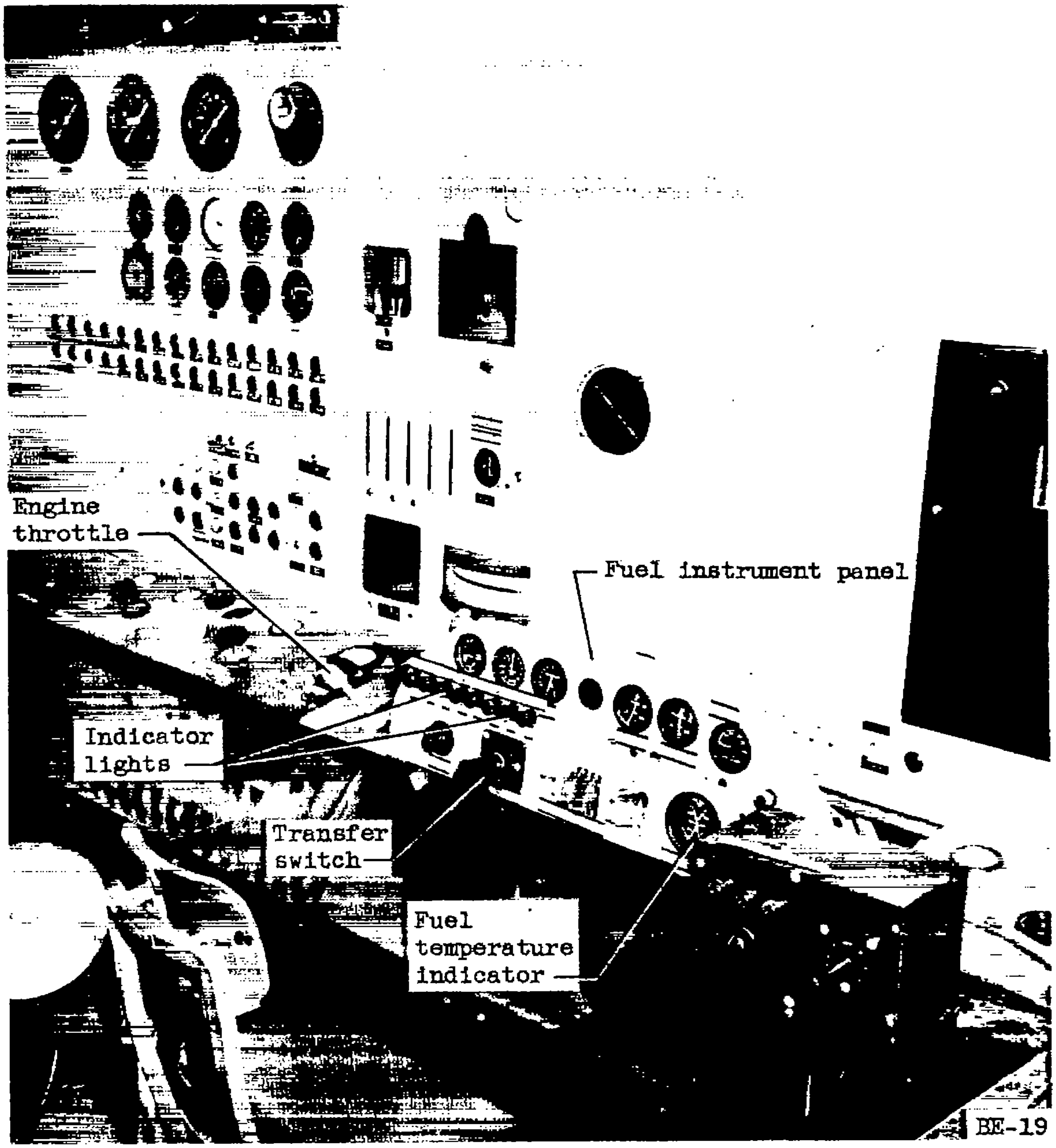
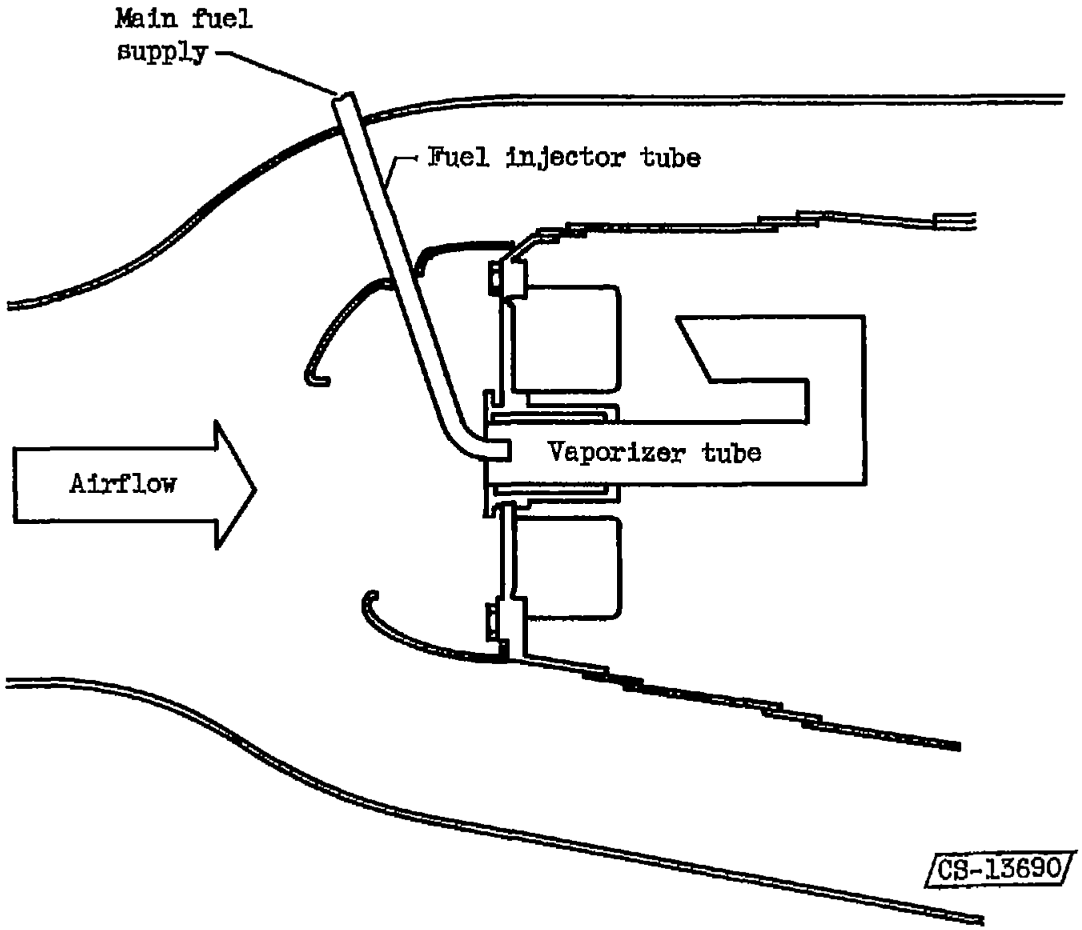
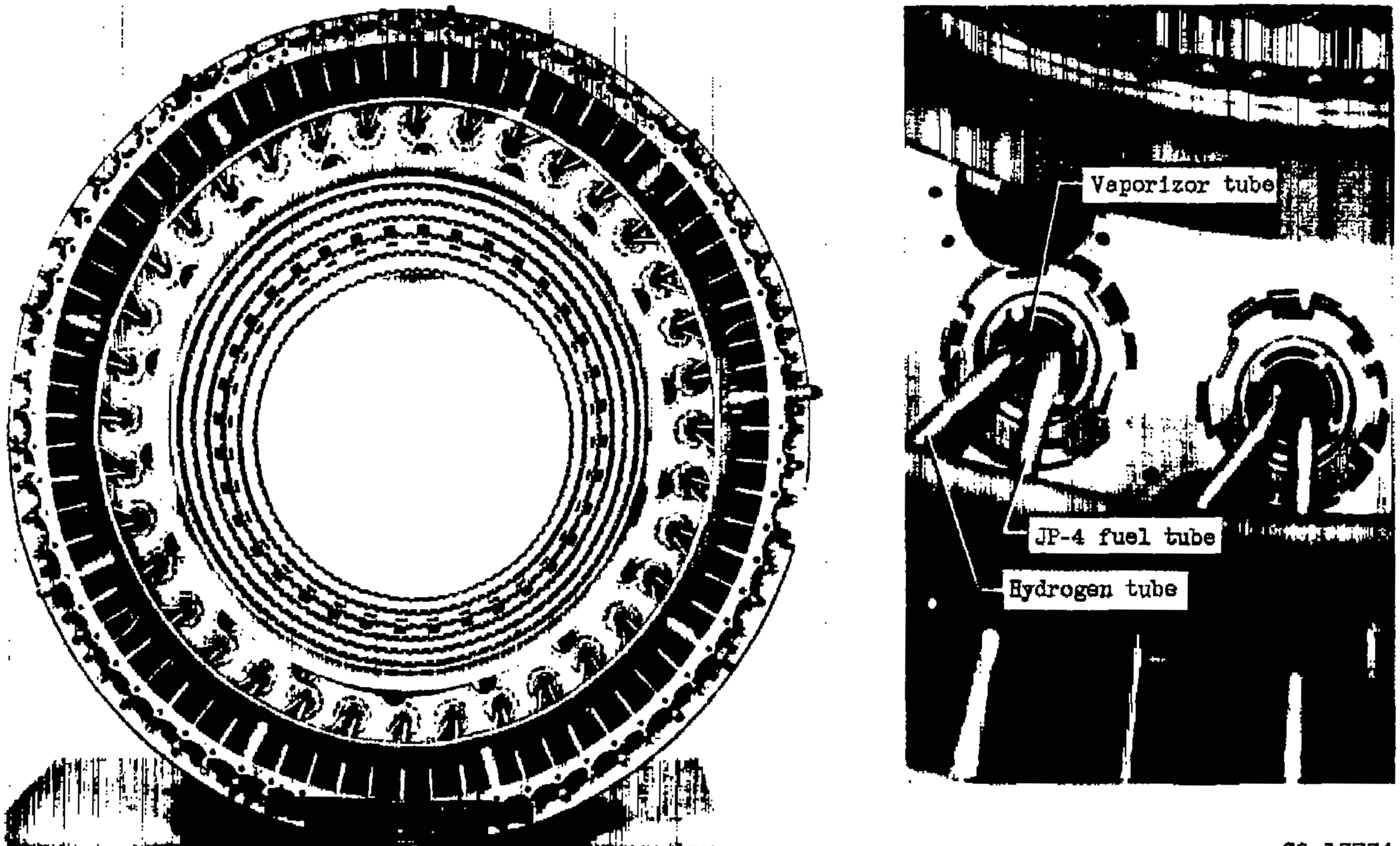


Figure 4. - Flight instrument panel installed in altitude-chamber control room.



(a) Schematic drawing of engine combustor before modification.

Figure 5. - Combustor modification for dual fuel operation.



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(b) Combustor inlet after modification.

Figure 5. - Concluded. Combustor modification for dual fuel operation.

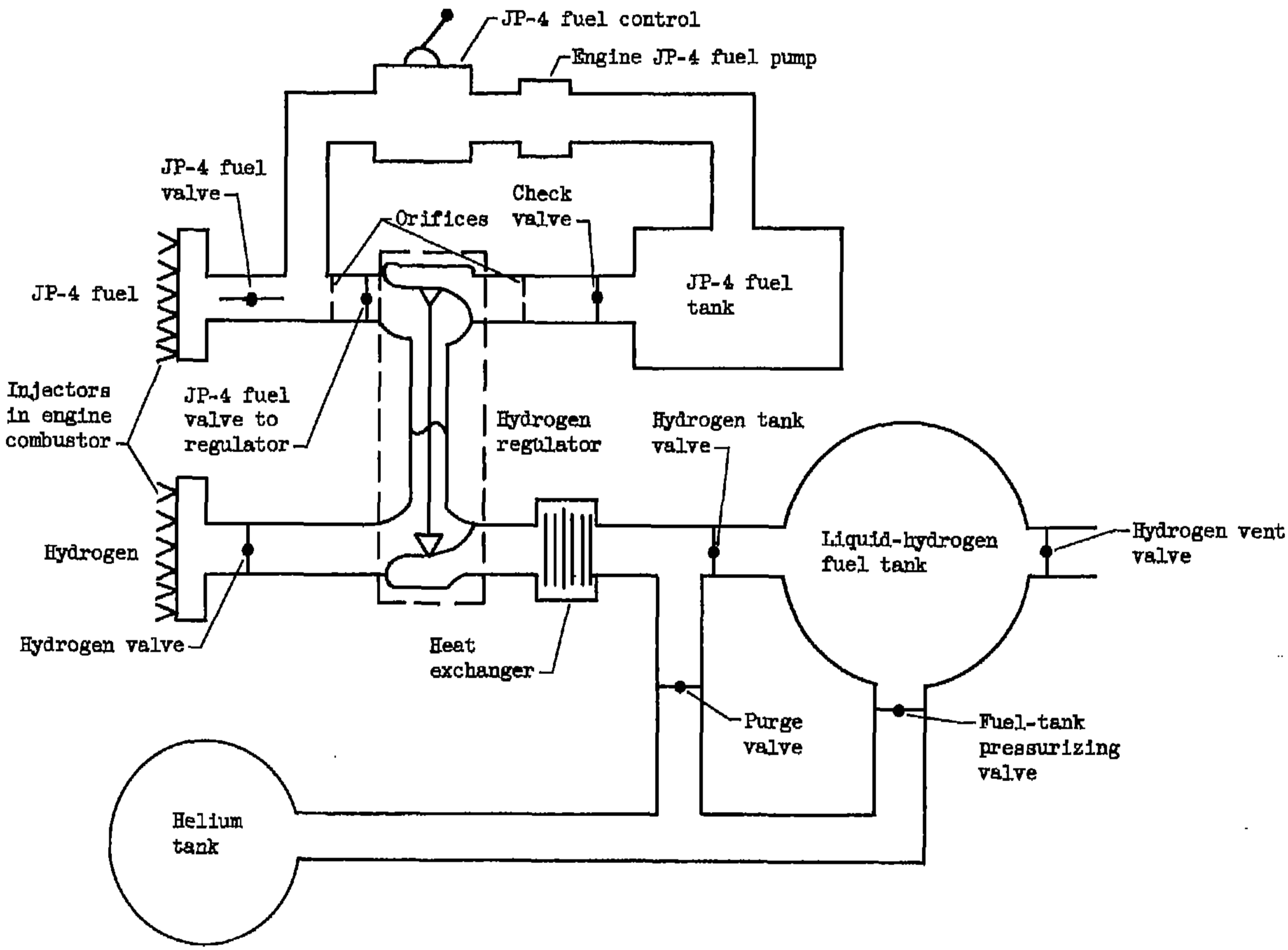
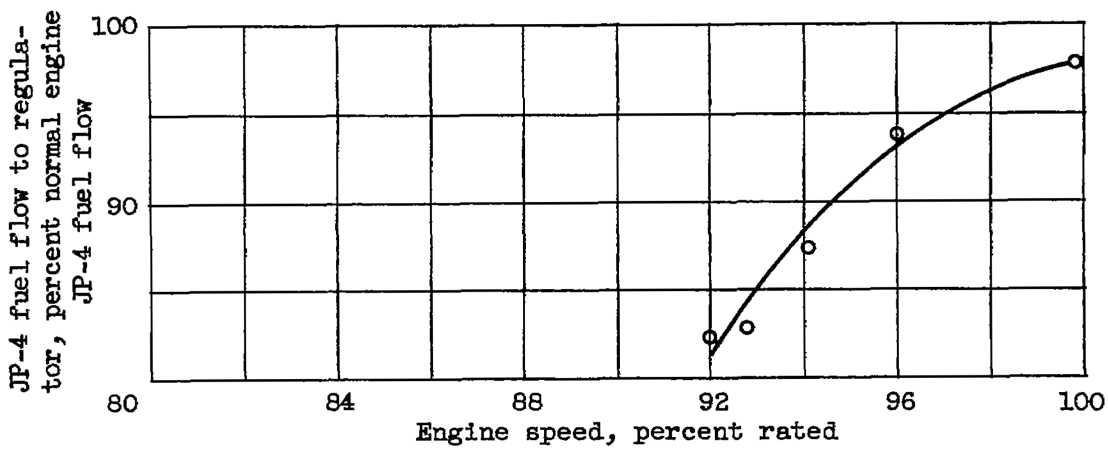
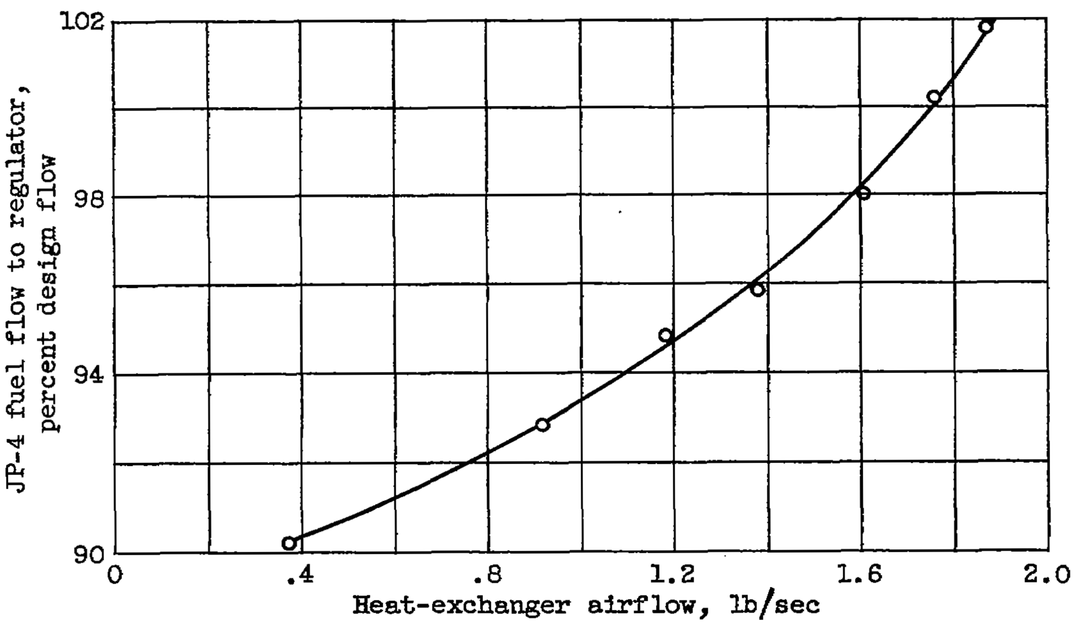


Figure 6. - Flow diagram for engine dual fuel system.



(a) Effect of engine speed at heat-exchanger airflow of 1.77 pounds per second.



(b) Effect of heat-exchanger airflow at rated engine speed.

Figure 7. - JP-4 fuel flow required by hydrogen regulator during steady-state operation.

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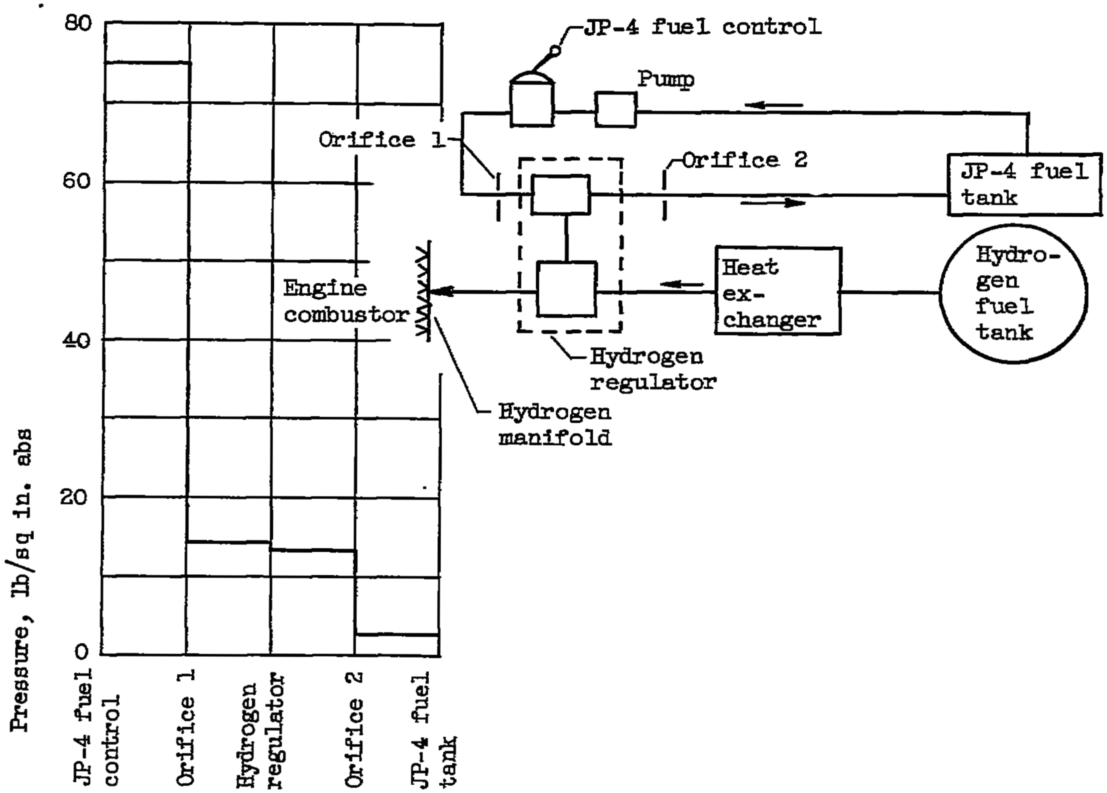
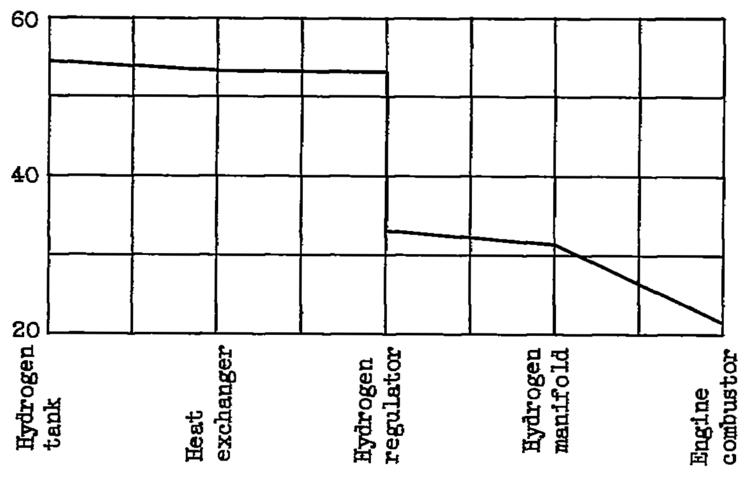


(a) Fuel pressures in JP-4 fuel system.



(b) Fuel pressures in hydrogen fuel system.

Figure 8. - Pressure levels in hydrogen fuel system during steady-state operation on hydrogen fuel. Altitude, 47,000 feet; flight Mach number, 0.75.

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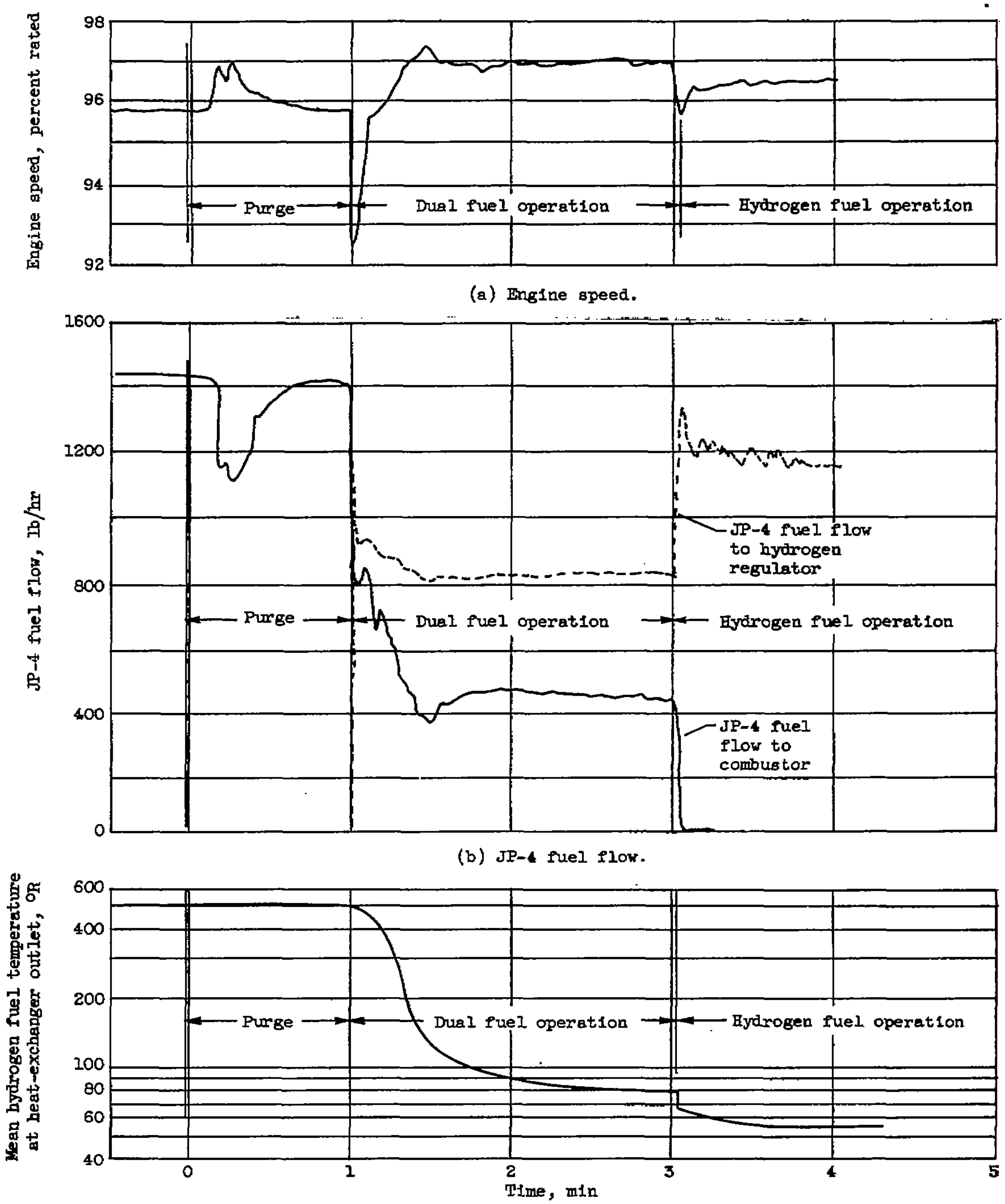


(a) Engine speed.

(b) JP-4 fuel flow.

(c) Mean hydrogen temperature at heat-exchanger outlet.

Figure 9. - Typical transition from JP-4 fuel to hydrogen. Altitude, 47,000 feet; flight Mach number, 0.75.

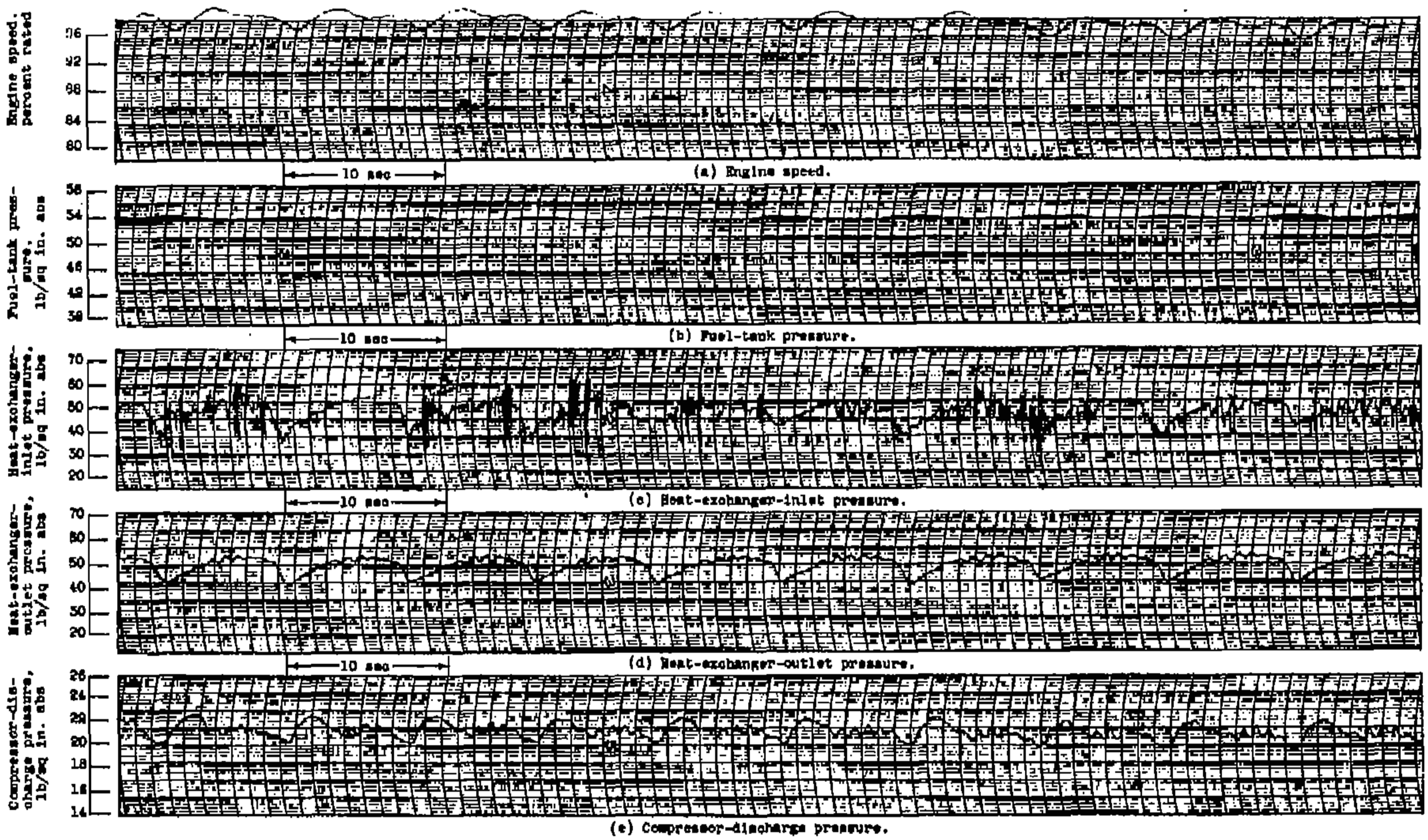
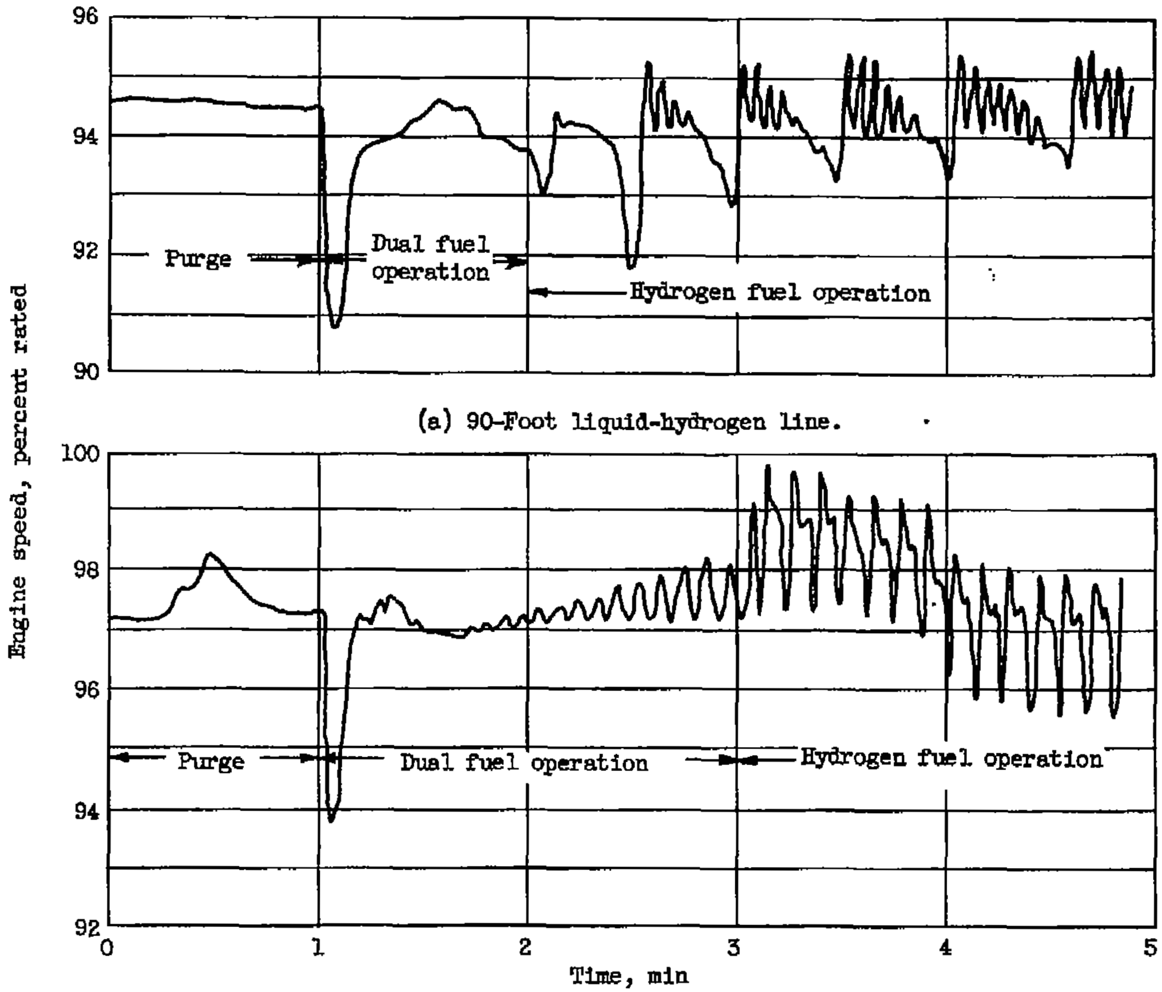
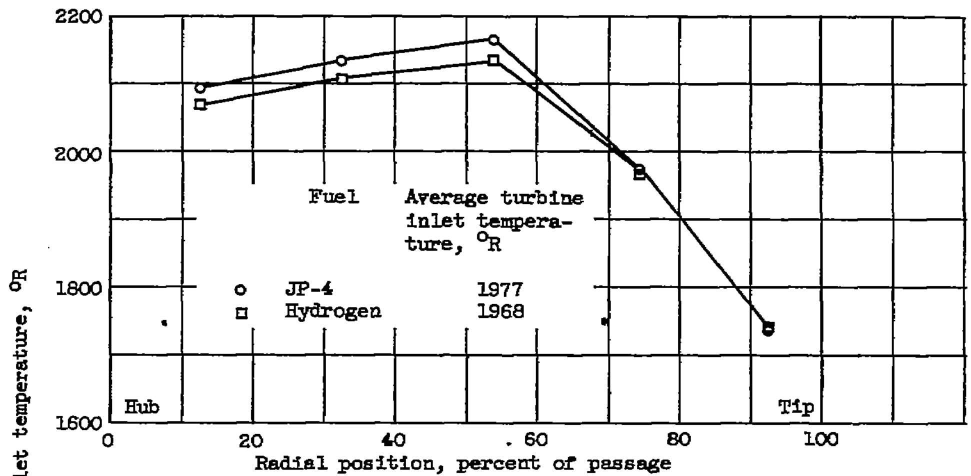


Figure 10. - Unstable operation with hydrogen fuel system. Altitude, 47,000 feet; flight Mach number, 0.75.

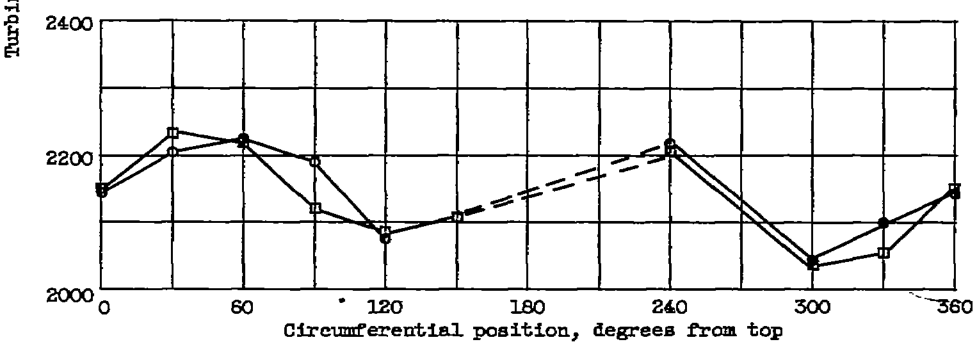


(b) 20-Foot liquid-hydrogen line.

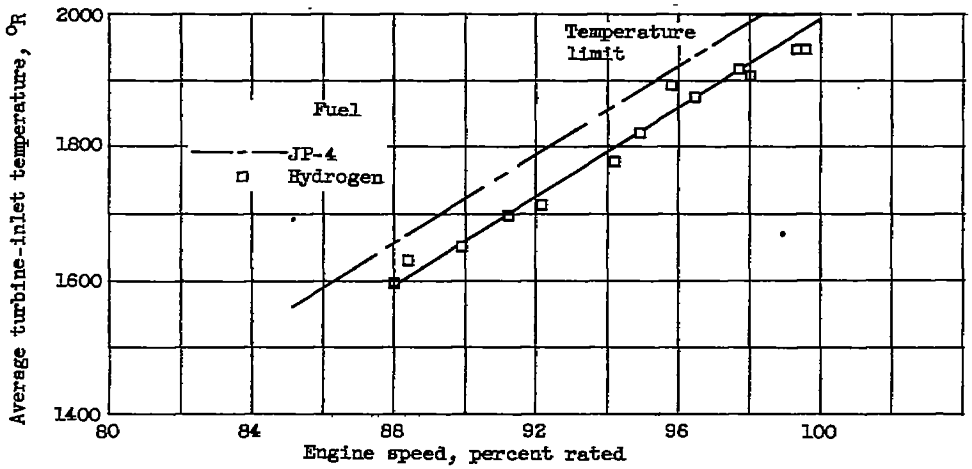
Figure 11. - Engine speed variations with hydrogen fuel lines of two lengths from tank to heat exchanger.



(a) Radial profile.

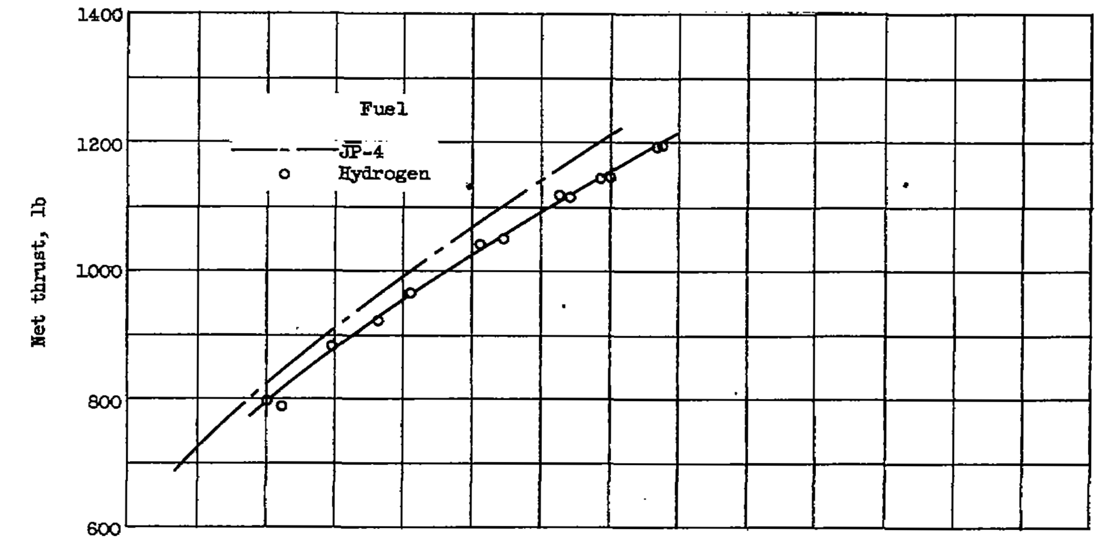


(b) Circumferential profile.

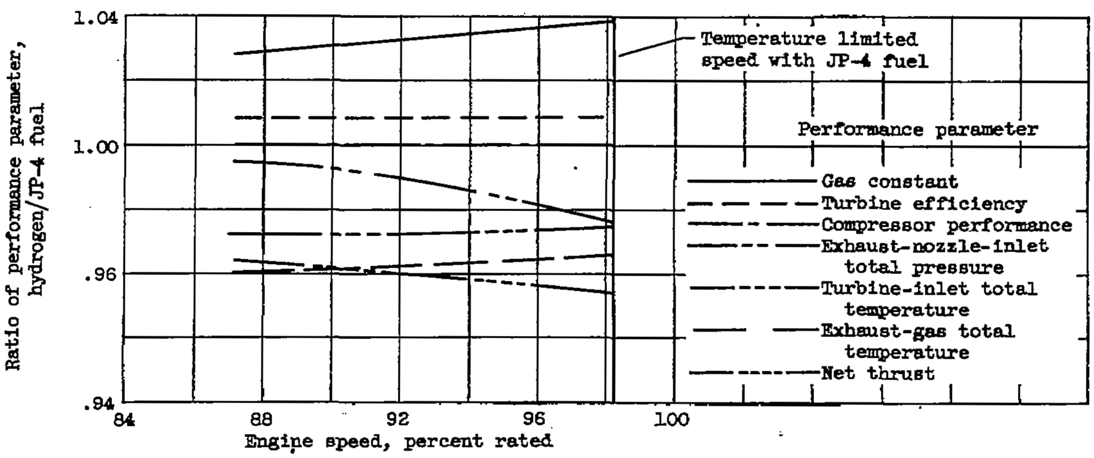


(c) Variation with engine speed.

Figure 12. - Comparison of turbine-inlet temperature obtained with hydrogen and JP-4 fuel.

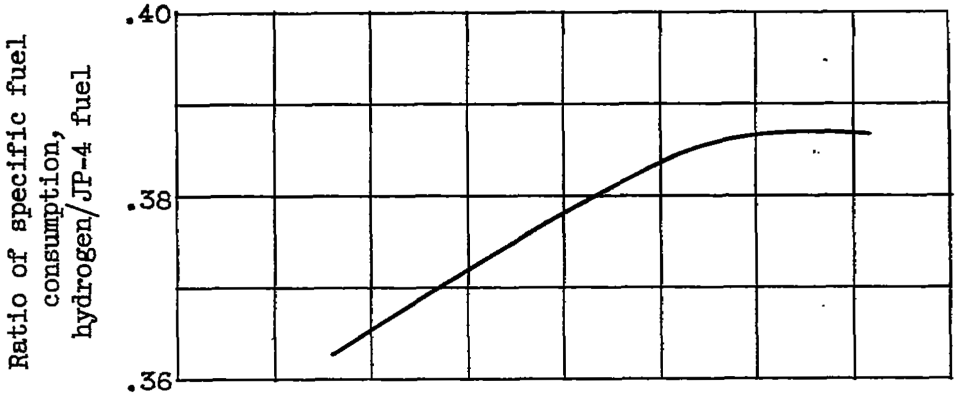


(a) Net thrust. Flight Mach number, 0.75.

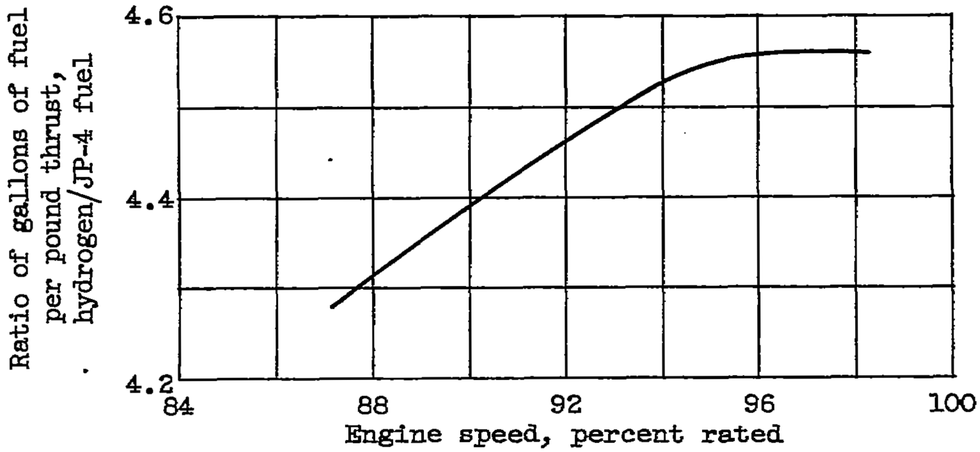


(b) Ratios of various engine parameters.

Figure 13. - Comparison of engine performance with hydrogen and JP-4 fuel.



(c) Ratio of specific fuel consumption.



(d) Ratio of volumetric specific fuel consumption.

Figure 13. - Concluded. Comparison of engine performance with hydrogen and JP-4 fuel.

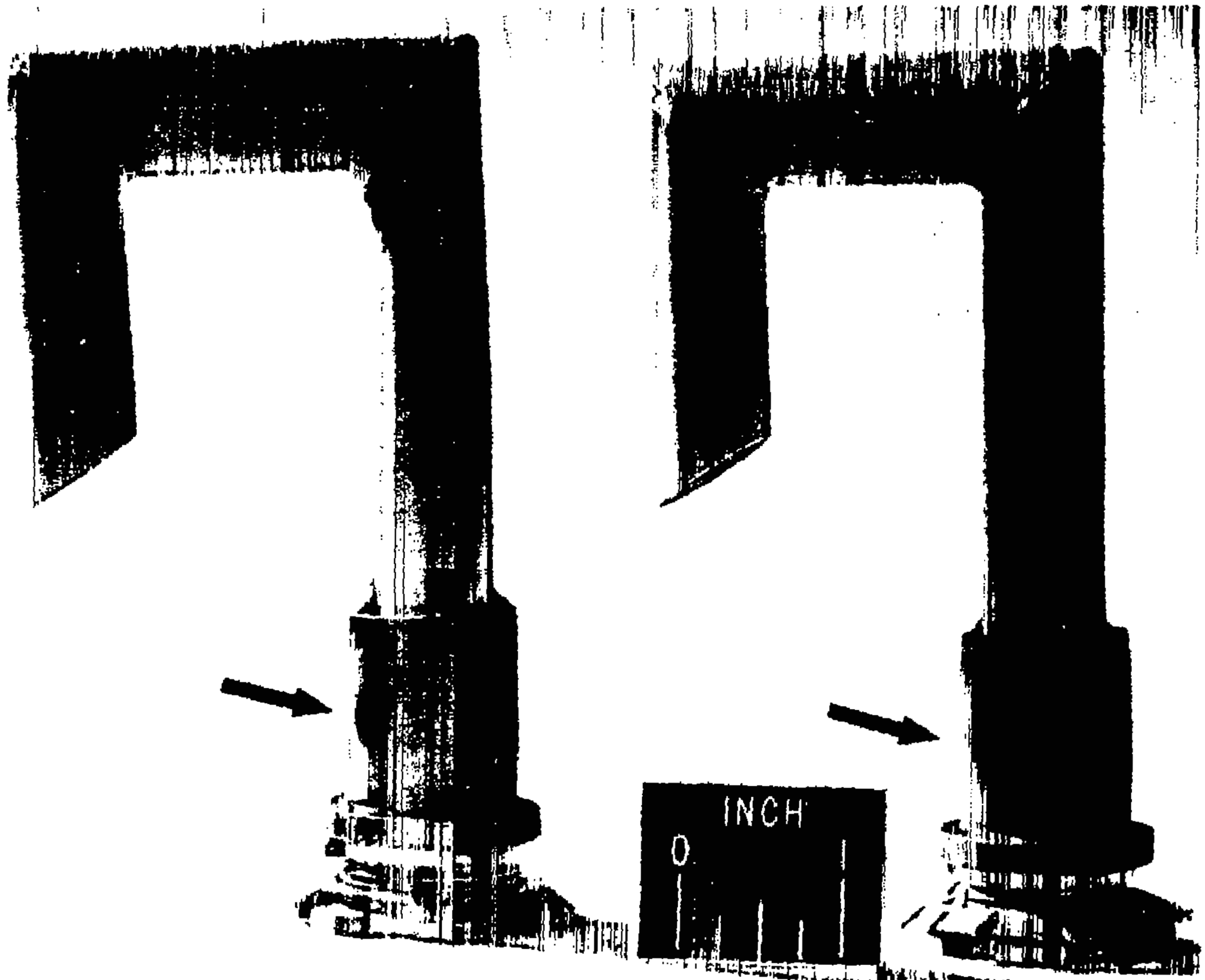


Figure 14. - Damage to two engine vaporizer tubes resulting from use of hydrogen.

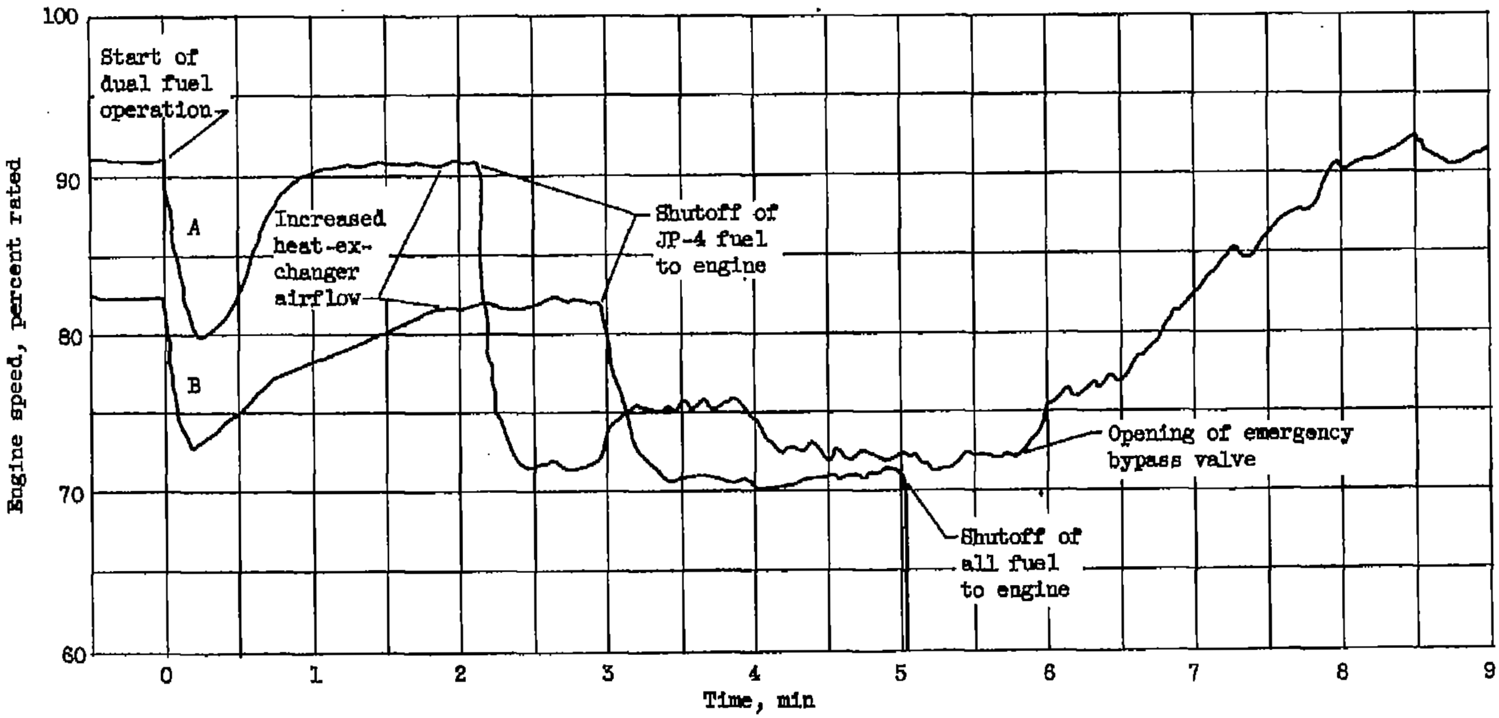


Figure 15. - Engine speed variations during transition with hydrogen regulator inoperative.

NACA - Langley Field, Va.